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The initial statement of work and planned milestones are reproduced. The status of effort and achievement are reviewed against initial targets. All objectives and milestones have been achieved.

A review of the research carried out is given, sample results provided and conclusions and recommendations from the work are summarized. These summaries provide only a brief pr6cis of the research programme, results and conclusions as detailed accounts are provided in two referenced and published technical reports.

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J A Ross

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Abstract

This document constitutes the final technical report under the terms of US Air Force Office of Strategic Research Grant No F49620-98-1-0167. This grant provided funding to undertake an experimental research programme to investigate the acoustic environment of single and tandem box cavities at high supersonic speeds to establish the effects of Reynolds number, Mach number and model scale.

The initial statement of work and planned milestones are reproduced. The status of effort and achievement are reviewed against initial targets. All objectives and milestones have been achieved.

A review of the research carried out is given, sample results provided and conclusions and recommendations from the work are summarised. These summaries provide only a brief précis of the research programme, results and conclusions as detailed accounts are provided in two referenced and published technical reports.

All results from the research programme are available on CD ROMs.

List of contents

List of Figures

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1 Statement of work.

The objectives of the research remained as in the original proposal and the Statement of Work is repeated below.

Objective : To investigate the aeroacoustic environment within open equipment cavities at high speeds and to define rules of scaling from small scale experimental data to flight scale.

Research Plan : The research programme will use the unique high Reynolds number capability of the DERA 3 ft x 4 ft supersonic wind tunnel to establish the acoustic properties of a family of both single and tandem cavity geometries, of constant length : depth ratio at different scale and over the wide range, 2×10^6 per foot to 10×10^6 per foot, of Reynolds number available from the 3 ft x 4 ft wind tunnel. The proposed test programmes would be carried out over the Mach number range $2.5 < M < 5.0$. Through the independent variation of Mach number and Reynolds number the separate effects Mach number, Reynolds number and model scale will be established and guidelines for extrapolation to full scale will be established. The research will also extend detailed knowledge of cavity acoustics to high supersonic speeds.

The research programme will use an existing DERA experimental model. This generic cavity model, already equipped with comprehensive facilities for steady state and unsteady pressure measurement, will be modified to create a series of three single cavity geometries at different scale, and a second series of dual tandem cavity geometries at different scale. For these two series of cavities, detailed measurements will be made of the highly unsteady pressure fluctuations within the cavities. These tests will cover the Mach number range $2.5<M<4.5$, and Reynolds number will be varied from 2×10^6 per foot to 10×10^6 per foot. Unsteady pressures will be measured with high response pressure transducers coupled to a high speed data acquisition system capable of sampling at 28,000 samples per second over 64 channels.

Analysis : Data analysis will be carried out using a powerful suite of software and will Identify through correlation techniques any influence on cavity acoustic field of tunnel acoustic signature and enable the removal of any such effects. Acoustic data will be processed by means of FFT techniques into PSDs and spectra. Key of key features of spectra such as discrete tones will be identified and correlation of observed tone frequencies with estimates (Rossiter) will be carried out. Any limitations of the Rossiter correlation at high Mach number will be identified.

Goals : Acoustic spectra, tone amplitudes and total sound pressure levels will be correlated with Mach number, model scale and Reynolds number and the independent effects of scale, Mach number and Reynolds number identified. Rules for the extrapolation of acoustic cavity data from experimental scale will be investigated.

Reporting : Reports detailing tests undertaken and results and conclusions from analysis will be produced.

2 Planned milestones.

The programme was planned to cover three years and the planned milestones were :

1.	Complete model modifications for first family of cavities	9 months
2.	Complete wind tunnel tests first series	11 months
3.	Complete analysis of data from first test	18 months
4.	Complete model modifications for second family of cavities.	19 months
5.	Complete second wind tunnel tests	20 months
6.	Report on first test series and analysis	24 months
7.	Complete analysis of data from second test series	27 months
8.	Final report detailing second test series and analysis and conclusions from all tests.	32 months

3 Status of effort and achievement.

3.1 All planned work has been completed. All planned milestones have been achieved broadly in line with the planned timescale.

3.2 The high speed unsteady pressure measurements made in the two sets of cavities (single and tandem cavities) have been analysed to identify the influence of Reynolds number, Mach number and model scale.

3.3 Results from the experimental programmes have been presented and discussed in two technical reports, for single cavities[1], and for tandem cavities[2]. Multiple copies of these reports[1 & 2] have been supplied to AFOSR. In addition to the two technical reports, full sets of the measured data from the single isolated cavities and the tandem cavities are available on two CD ROMS. On these, unsteady pressure data from cavity ceiling, front walls, rear walls and the leading flat plate for all measurement locations are provided in spectral form. Data are provided in EXCEL comma separated variable (csv) format in terms of root mean square (rms) amplitude against frequency and also in terms of power spectral density (psd) against frequency. Copies of the CD ROMs containing data from the single cavity tests and the tandem cavity tests have been supplied to AFOSR.

4 Summary of experimental programmes.

4.1 High speed wind tunnel.

4.1.1 The tests were carried out in the DERA High Supersonic Speed Wind Tunnel, a continuous flow pressurised wind tunnel with a test section 4 ft high and 3 ft wide. The layout of the tunnel is shown in Figure 1. The Mach number range, continuously variable

from M=2.5 to M=5.0, is controlled by flexible roof and floor liners. Stagnation pressure can be varied between 0.1 and 12 bars and stagnation temperatures can be controlled up to 150°C. Reynolds number can be varied up to 12 million per foot depending on Mach number.

4.2 Cavity model.

4.2.1 A view of the cavity is shown sting-mounted in the DERA 3 ft x 4 ft wind tunnel inFigure 2.

4.2.2 For the initial single cavity tests a family of three isolated empty rectangular cavities was investigated. The three cavities had a common length to depth ratio (L/D) of 5.0 and common width to depth (W/D) of 1.0. Cavity lengths were 20 inches, 10 inches and 5 inches respectively. For all cavities width was identical to depth and these values were 4 inches, 2 inches and 1 inch respectively.

4.2.3 In the second test phase two sets of isolated empty tandem rectangular cavities were investigated. The four cavities had a common length to depth ratio (L/D) of 5.0 and common width to depth (W/D) of 1.0. For the larger tandem pair, cavity lengths were 10 inches, and for the smaller pair lengths were 5 inches. Cavity depths, widths and the separations between front and rear cavities were 2 inches and 1 inch respectively. As one of the objectives was to compare and contrast the results with the equivalent results[1] from single cavities, the cavity pairs were designated 'medium' and 'small' as these were the designations given to identical sized cavities in the earlier work with single cavities

4.2.4 The experimental cavities were pre-formed within a 'sump-pan', shown in Figure 3 and Figure 4, which was located within the main body of the cavity model. Each cavity within the 'sump-pan' was equipped with a set of static and unsteady pressure instrumentation. The chosen experimental cavity configuration was exposed by fitting a cover plate with apertures matching the desired cavity layout. The three single cavity configurations and two tandem cavity configurations created in this way are shown in Figure 3 andFigure 4 . From these figures it is seen that for all of the single cavities and both tandem pairs the leading edge of the front cavities are located at a common longitudinal station on the model, 31 inches aft of the leading edge of the model.

4.2.5 Each cavity was instrumented with a large number of steady (time-averaged) pressure and unsteady measuring stations. Locations of both static and unsteady measuring locations are specified in detail in the respective technical reports[1 & 2]. External to the cavities a row of 28 static pressure stations was installed on the flat plate forward of the cavities at a lateral location 1 inch from the model centre line, and this row continues with an additional 14 static pressure stations aft of the rear of the longest cavity pair. Two high frequency response unsteady pressure transducers were located on the front flat plate centre line 3 inches and 7inches forward of the cavity leading edge station. Within each cavity both static pressure and unsteady pressure instrumentation was similar. Each cavity had 20 static pressure measurement points evenly distributed along the ceiling centre-line and along the mid-height point of both side walls. In addition all cavities had a single vertical row of four static pressure points on the centre-line of the front and rear walls. On all cavities unsteady pressures were measured at 10 locations on the cavity ceiling with the row being located at the 25% width location. In addition the front and rear walls of all the cavities each featured 2 unsteady pressure transducers situated at different depths on the 25% width location.

4.2.6 Boundary layer transition was fixed near the leading edge of the forward flat plate to ensure that the approach boundary layer was fully turbulent at all conditions in the test programme. Transition was fixed on the plate using a band of sparsely distributed 0.13

mm to 0.15 mm diameter ballotini set in a very thin layer of epoxy resin. The leading edge of the transition band was located 40 mm from the leading edge with a 4 mm streamwise width.

4.2.7 Setting of the model, to ensure that the forward flat plate was aligned accurately with the wind tunnel axis was accomplished by means of an inclinometer capable of measuring to 1 second of arc.

4.3 Data acquisition.

4.3.1 All steady (time-averaged) pressures were recorded using S-Type Scani-valves. Pressures were distributed over eight 48 way modules in order to place pressures into separate groups within which measured pressures would be of similar magnitude. The ultimate accuracy (due to non-linearity and hysteresis) of the 15PSI transducers fitted to the Scani-valves was quoted as ±0.04% of full scale. When additional allowance is made for other small inaccuracies in the data acquisition system uncertainty is increased to ±0.06% of the full scale transducer range, giving an uncertainty in measured time-averaged pressures of ±0.009PSI.

4.3.2 Unsteady pressures were measured by 25 pounds per square inch (PSI) range Kulite high frequency response pressure transducers. Unsteady pressures were sampled and recorded using the DERA unsteady pressure recording and analysis system, PRESTO III. The system is capable of simultaneously sampling, recording and analysing up to 64 channels of unsteady data, up to a sampling rate of 150KHz per channel, subject to a maximum total throughput of approximately 1.4 million samples per second.

4.3.3 Data were recorded in the form of time histories. The sample rate was chosen to be at least twice (approximately 2.4 times) that of the highest frequency anticipated for any condition. Anti alias filters were set to the highest frequency of interest for any condition. In choosing sample rates, the formula developed by Rossiter[3] was used to provide an estimate of tone frequencies likely to be present in the cavities. As sampling rate was varied the recording data block size was also varied in order to retain an on-line frequency resolution (given by sample rate/block size) of around 15Hz.

4.3.4 During post-test processing, time history data were analysed on the basis of block lengths of 2048 samples. Acoustic spectra were derived through ensemble averaging the spectral data from the Fourier analysis of subsequent blocks over the complete sample time history. This process led to a range of frequency resolutions, which varied with condition and configuration, from approximately 7 Hz for the lower sample frequency cases to 17 Hz for the higher sample frequency conditions. Full details of sample rates, block sizes and number of blocks recorded are provided in references 1and 2.

4.4 Test conditions.

4.4.1 All cavity configurations used in both test phases were tested at Mach numbers of 2.5, 3.0, 3.5, 4.0 and 4.5. At each Mach number cavity acoustic measurements were made at Reynolds numbers of 2 million per foot, 4 million per foot, 6 million per foot, 8 million per foot and 10 million per foot, except at M=3.0 and M=3.5 where the tunnel envelope limited Reynolds number to 6 million per foot and 8 million per foot respectively.

4.5 Sample results.

4.5.1 Figure 5 shows a sample of results in spectral form at a single measurement station on the cavity ceiling, where the variation of unsteady pressure rms amplitude non-dimensionalised by free-stream dynamic pressure with Strouhal number. These results

illustrate the variation of the acoustic spectra with Mach number for the large and medium sized single cavities.

4.5.2 An example of the variation of total sound level along the length of the cavities is shown in Figure 6. Results shown the variation of total sound pressure level with cavity scale for the large, medium and small single cavities at Mach numbers of 2.5, 3.0 and 3.5.

5 Summary of conclusions and recommendations.

5.1 Single isolated cavities.

5.1.1 All three cavities generated intense unsteady pressure environments. Acoustic spectra were characteristic of aerodynamically 'open' (or 'deep') cavities, with the appearance of a number of high level discrete tones superimposed on a lower level broadband background. As Mach number increases from 2.5, tone frequencies tend to become less distinct, and at the highest Mach number of 4.5 only the most dominant tone was clearly visible.

5.1.2 The frequency of the discrete tones can be approximately predicted by the well known empirical formula of Rossiter[3]. Closest agreement with predicted frequencies was obtained for the smallest cavity geometry. As cavity size (length) increases measured tone frequencies gradually increase above the predicted values.

5.1.3 As in many other cavity flow studies, one of the measured tone frequencies was significantly greater in amplitude than the others. In these tests at high Mach number the fourth tone frequency in the series was the dominant tone. This contrasts with much of the previous work at subsonic, transonic and lower supersonic speeds where most commonly the second tone, but occasionally the third has been found to dominate. There is, however, other evidence[4] from tests at Mach numbers comparable to these tests of a dominant fourth tone.

5.1.4 Within the Reynolds number range explored there is no variation in the character of the acoustic environment with Reynolds number and no change in the discrete tones observed. The results suggest that, provided Reynolds number based on cavity length is greater than 3.5 million, then tone amplitudes are independent of Reynolds number. At lower Reynolds numbers tone amplitudes are reduced. In the case of the lower level broadband background, Reynolds numbers based on cavity length greater than 6.67 million would appear to be required to ensure Reynolds number independence. However, for Reynolds numbers above 5 million, variation with Reynolds number is small. At lower Reynolds numbers broadband background levels decrease.

5.1.5 For all of the cavity geometries, fluctuating pressure levels (both discrete tones and broadband background) fall off rapidly as Mach number is increased. Combining results from the largest cavity with previous tests on this cavity over a range of lower Mach numbers suggests that acoustic levels reach a maximum around M=1.3 and fall significantly as Mach number is increased above this value; a result in accord with work done elsewhere.

5.1.6 The effect of cavity scale on the fluctuating pressure environment is overall quite complex. Considering first an analysis based at a single unsteady pressure location near the rear of the cavities, where unsteady levels are at their highest levels. For the medium and smallest of the cavities there is a reduction (or roll-off) in tone amplitude as cavity size decreases. This roll-off can be related to the ratio of the thickness of the approach

boundary layer to cavity length as first proposed by Shaw[5]. Results are in accord with the suggestion by Shaw[5] that for values of $\delta/L>0.03$ reduction in tone amplitude can occur, albeit that the range of cavity sizes used does not allow the precise value at which the roll-off begins to be determined. Similar conclusions can be made at some other points within the cavities, for instance $X/L=0.25$.

5.1.7 However, in examining the acoustic behaviour along the length of the cavities in terms of total sound pressure level (but noting that these values are in themselves dominated by the magnitude of the tone frequencies), the observed roll-off behaviour varies along cavity length. Over significant portions of the cavity length ($0.3<X/L<0.9$), fluctuating pressure levels measured in the smallest cavity are greater than for the medium cavity. Indeed at higher Mach numbers ($M\geq3.5$) there are localised regions ($0.45<X/L<0.65$) where unsteady pressure levels are highest for the smallest cavity. These changes are also evident in the acoustic spectra. Thus, it is concluded that the variation of fluctuating pressure levels with cavity scale is more complex than is indicated by consideration of this variation at isolated locations within the cavities.

5.1.8 Nevertheless, because maximum unsteady pressure levels occur towards the aft end of a cavity, the variation of amplitude with scale, based on consideration of locations in the aft 5% of cavity length, does provide a useful guide as to the cavity size required to capture maximum levels.

5.2 Tandem cavities.

5.2.1 As in the case of the single cavities all of the cavities generated intense unsteady pressure environments. Acoustic spectra were characteristic of aerodynamically 'open' (or 'deep') cavities, with the appearance of a number of high level discrete tones superimposed on a lower level broadband background. As Mach number increases from 2.5, tone frequencies tend to become less distinct, and at the highest Mach number of 4.5 only the most dominant fourth tone is clearly visible. Tone frequencies were identical for the front and rear cavities.

5.2.2 The frequency of the discrete tones in both front and rear cavities can be approximately predicted by the well known empirical formula of Rossiter[3]. Closest agreement with predicted frequencies was obtained for the smallest cavity geometries. As cavity size (length) increases measured tone frequencies become greater than the predicted values.

5.2.3 As for the single cavities one of the measured tone frequencies was significantly greater in amplitude than the others. Again the fourth tone was most dominant

5.2.4 Within the Reynolds number range explored there is no variation in the character of the acoustic environment with Reynolds number and no change in the discrete tones observed. The results are in agreement with the earlier single cavity tests which suggest that, provided Reynolds number based on cavity length is greater than 3.5 million, then tone amplitudes are independent of Reynolds number. At lower Reynolds numbers tone amplitudes are reduced. In the case of the lower level broadband background, Reynolds numbers based on cavity length greater than 6.67 million would appear to be required to ensure Reynolds number independence. At lower Reynolds numbers broadband background levels decrease.

5.2.5 For all of the cavity geometries, fluctuating pressure levels (both discrete tones and broadband background) fall off rapidly as Mach number is increased. This is in accord with the earlier results for single cavities, where together with data from tests at lower Mach numbers it was verified that fluctuating pressure levels were at a maximum at

around M=1.3, and fell progressively as Mach number was increased above M=1.3.

5.2.6 The major difference between front and rear cavities was in the higher levels of fluctuating pressure measured in the rear cavities. Total sound pressure levels in the rear cavities were up to 10dB higher (three times) than those measured in the front cavities. RMS amplitudes of the fluctuating pressure in parts of the frequency spectra were up to 17dB higher (seven times) than for the front cavities.

5.2.7 The effect of cavity scale on the fluctuating pressure environment is overall quite complex. As the tests were restricted to only two sets of cavities, and both were sufficiently small to be subject to decreased unsteady pressure levels associated with approach boundary thickness, detailed analysis was not possible. However, for both the medium and small front cavities SPL and spectral characteristics were nearly identical to those found for the identical single cavities tested earlier.

5.2.8 It is evident that for tandem cavities, typical of those tested at high supersonic Mach number, with length to depth ratios of around 5 and cavity separations of around 10% of cavity length, that there is no influence of the rear cavity on the front cavity, but that the presence of the forward cavity significantly influences the rear cavity. This influence results in greatly increased levels of unsteady pressures in the rear cavity. Characteristics of the rear cavity are, however, not influenced by the front cavity, in that it exhibits the same characteristic tones and a typical, but elevated, broadband background.

5.3 Recommendations.

5.3.1 As a result of the programmes completed a number of areas have been identified where further investigation is recommended. These recommendations are fully detailed in references 1 and 2 and a brief summary is provided here.

5.3.2 For single cavities further investigation of the effect of model scale is recommended. In particular, this work should further investigate the influence of the approach boundary layer condition on the acoustic signature generated within a cavity. In this work boundary thickness could be artificially altered through a range of values, with boundary layer thickness at each thickness being measured.

5.3.3 It is also recommended that further studies of the effects of model scale on a series of similar model geometries with a smaller change of scale between configurations than in the work reported would be valuable. This would enable an accurate determination of the size of model where the acoustic environment shows the first signs of "roll-off".

5.3.4 For tandem cavities it is recommended that further work should be done to investigate the effects of cavity scale on the acoustic levels and characteristics of the rear cavities. This would require additional tests with at least one further tandem pair, large enough to ensure that the ratio of approach boundary thickness to cavity length was less than 0.03, to avoid any reduction in unsteady pressure levels.

5.3.5 It is also recommended that further work should be undertaken to investigate the effect of the separation between front and rear cavities. As it has been postulated that increased unsteady pressure levels in the rear cavities are due to the rear flowfield being initially set up through the influence of the flowfield of the front cavity, the length of the inter-cavity gap could affect this significantly. To establish the effects of the inter-cavity gap, a parametric study varying this gap from very small up to about 25% of cavity length is recommended.

5.3.6 Finally it is recommended that further tests on tandem cavities, with front and rear cavities of significantly different length to depth ratio would provide important information on the mechanism leading to increased unsteady pressure levels in the rear cavity.

6 Personnel.

6.1 The work funded by Grant No F49620-98-1-0167 has bee supervised and controlled by the Principle Investigator Dr J A Ross with support from J W Peto and J Odedra the researchers identified in the original proposal. Miscellaneous effort from instrumentation, wind tunnel and workshop staff as identified in the initial proposal also contributed to the successful conclusion of the work.

7 Publications.

7.1 Two DERA technical reports have been published detailing the results and analysis arising from the experimental programmes on single and tandem cavities. The authors of these reports were the Principle Investigator and the researchers identified in the proposal. Details of these reports are provided as references 1 and 2.

7.2 In addition to the published technical reports full sets of experimental data from the two experimental phases are available on CD ROMs.

7.3 The technical reports and CD ROM data have been provided to AFOSR.

8 Acknowledgement.

8.1 All work described was funded by means of Grant No F49620-98-1-01670 from the United States Air Force Office of Strategic Research under the Technical Management of Dr Leonidas Sakell whose help and support is gratefully acknowledged.

9 References

1. J. A. Ross, J. W. Peto, J. Odedra, "Cavity acoustic measurements at high speeds", DERA/MSS/MSFC2/TR000173, March 2000.

2. J. A. Ross, J. W. Peto, J. Odedra, "Acoustic measurements in tandem cavities at high speeds", DERA/MSS/MSFC2/TR002385, Sept 2000.

3. J. E. Rossiter, "*Wind tunnel experiments on the flow over rectangular cavities at subsonic and transonic speeds*", RAE TR 64037, Oct. 1964

4. S. W. Perng, D. S. Dolling, "*Attenuation of pressure oscillations in high speed cavity flow through geometry changes",* Centre for Aeromechanics Research, Aerospace Engineering Mechanics Dept, University of Texas, Austin, TX 7812-1085, Oct 1996.

5. L. L. Shaw, "Scale effect on the flow induced acoustic environment in cavities", WRDC-TM-89-159-FIBG, Feb 1989.

10 List of symbols and abbreviations.

Ceil	Abbreviation used in figures indicating a cavity ceiling pressure.
D	Cavity depth.
L	Cavity length.
M	Mach number.
R	Reynolds number.
SPL	Sound pressure level, (dB) referenced to free-stream dynamic pressure (q).
U	Free stream velocity, (Feet per second).
W	Cavity width.
X	Longitudinal co-ordinate. Positive in streamwise direction. Origin at front edge of cavity.
dB	Decibel logarithmic unit of pressure referenced to free-stream dynamic pressure (q), given by $20*\log(P_{rms}/q)$.
d	Boundary thickness where $U/U_{inf}=0.995$
f	Frequency, (Hz).
fL/U_{inf}	Strouhal number or reduced frequency
inf	Subscript indicating free-stream value
q	Free-stream dynamic pressure
rms	Root mean square.

11 Figures

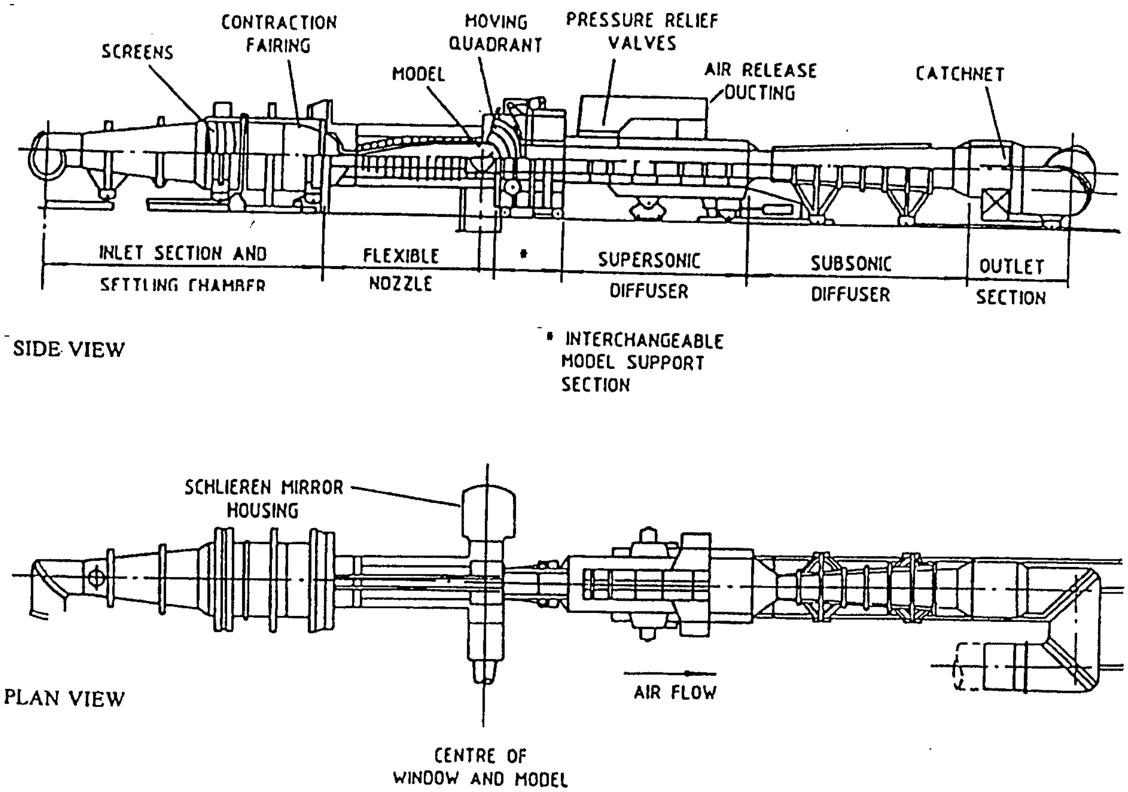


Figure 1 Layout of DERA 3 ft x 4 ft wind tunnel.

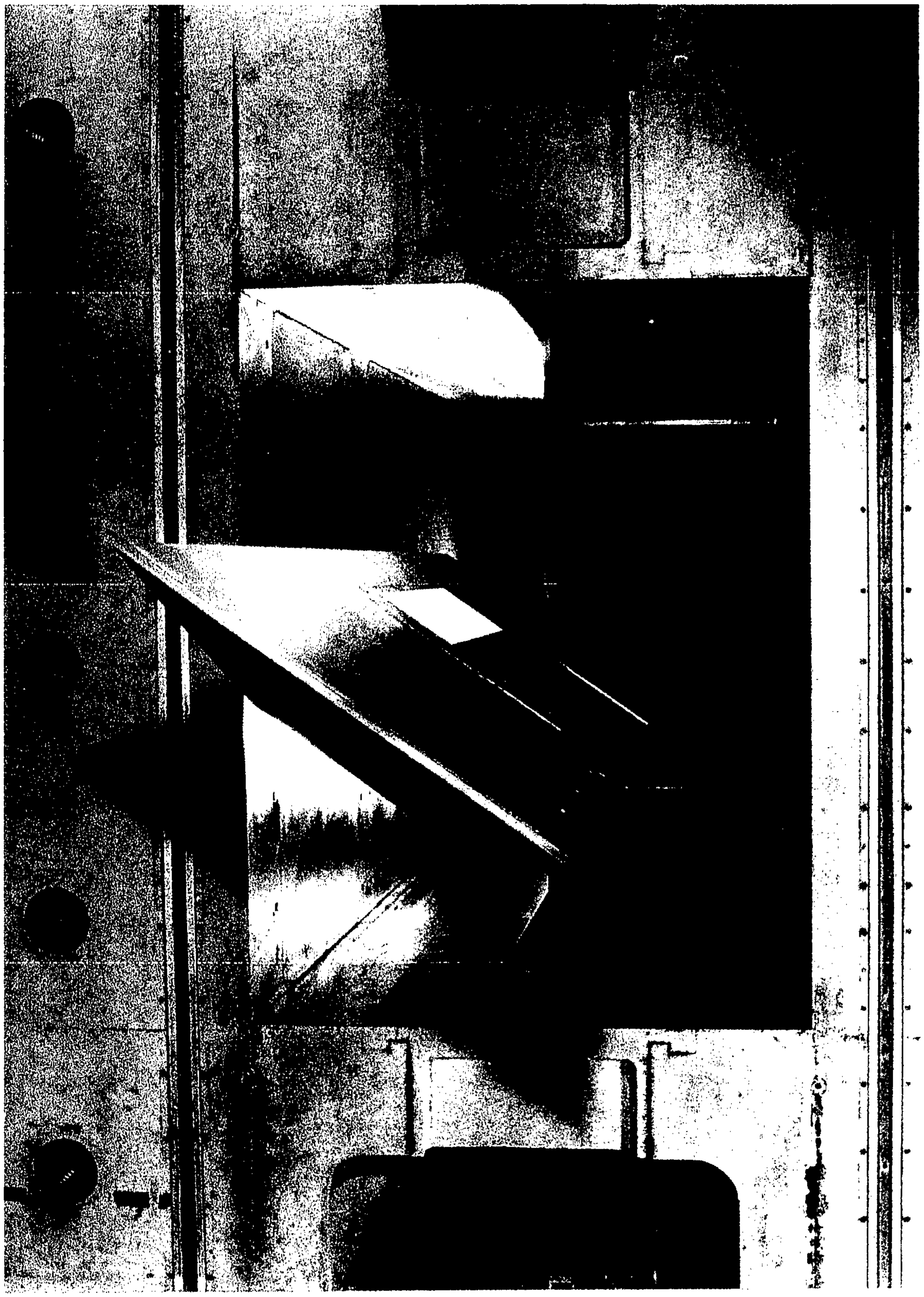
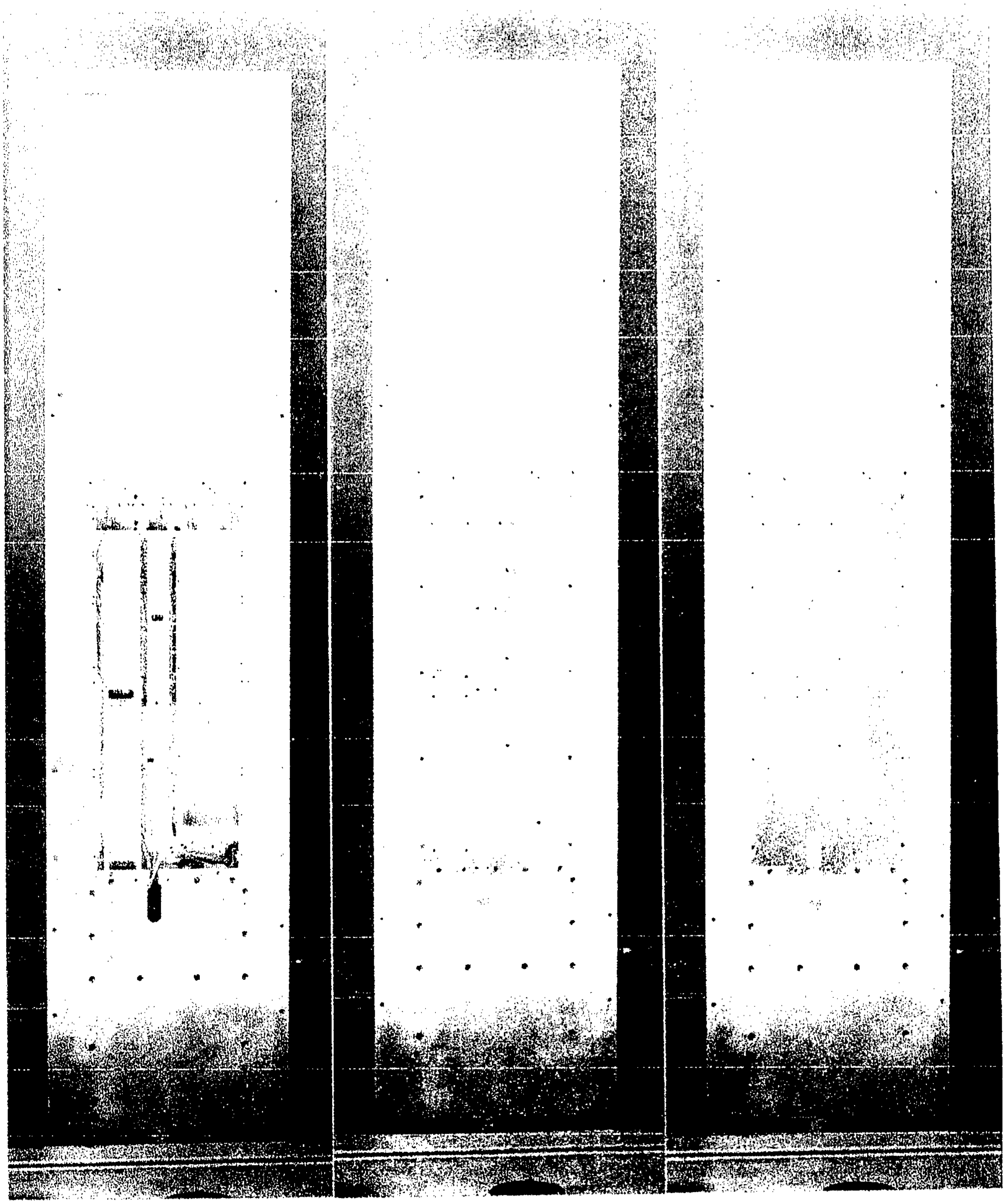


Figure 2 Cavity model in DERA 3 ft x 4 ft wind tunnel.

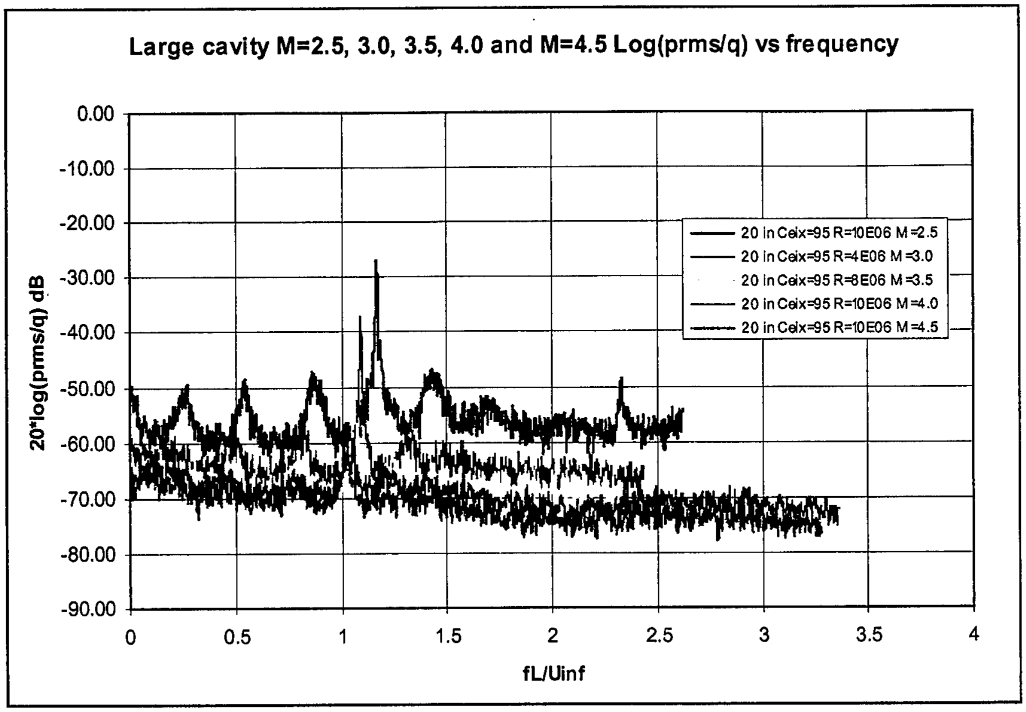
a) Sump Pan b) 20 in Large Cavity c) 10 in Medium Cavity d) 5 in Small Cavity

Figure 3 Layout of 'sump-pan' and three single cavities.



a) Sump Pan | b) 10 in Medium Tandem Pair | c) 5 in Small Tandem Pair

Figure 4 Layout of 'sump-pan' and two pairs of tandem cavities.



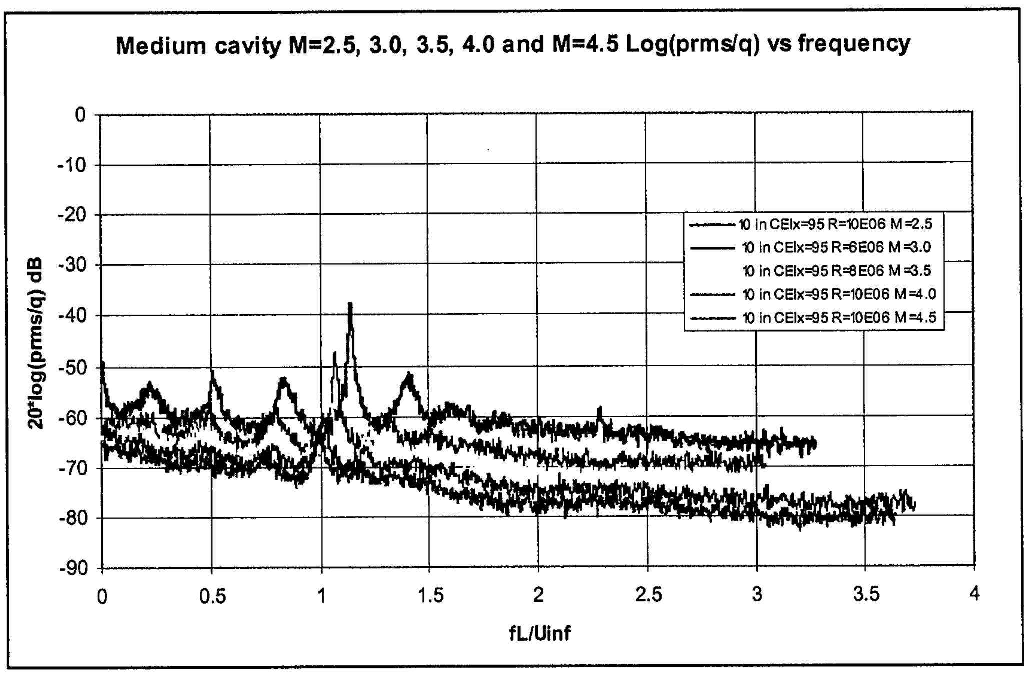
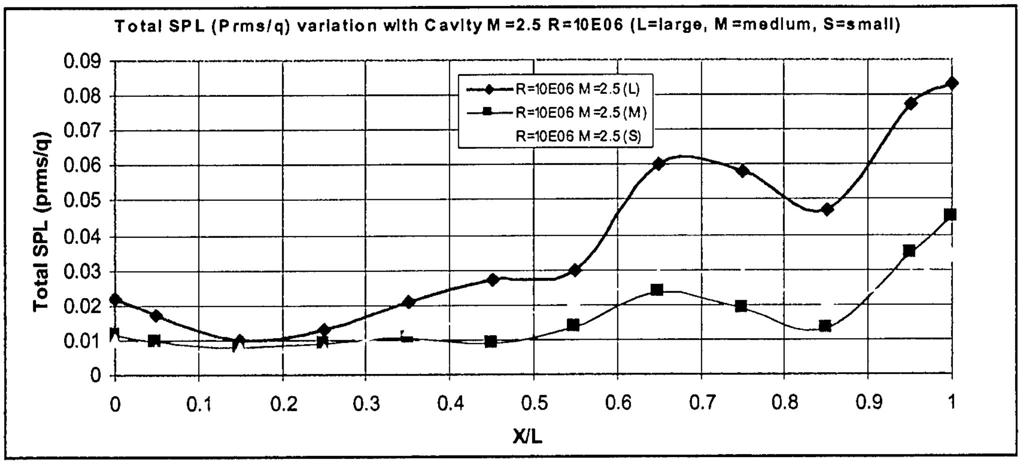
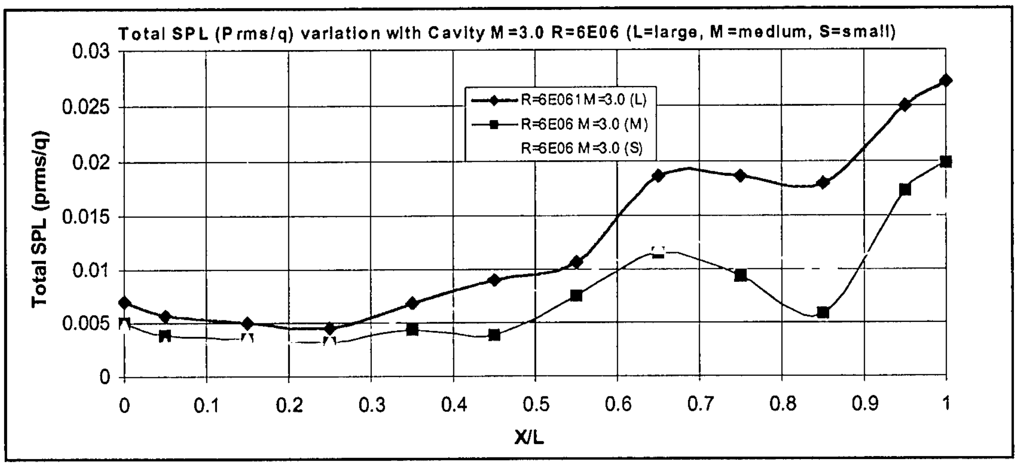


Figure 5 Large and medium single cavities: variation of acoustic spectra with Mach number.





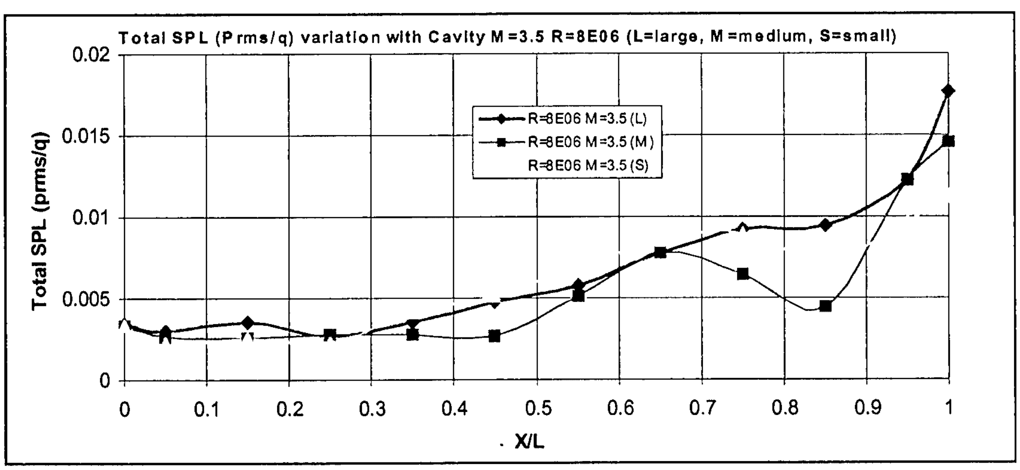


Figure 6 Single cavities: variation of total sound pressure level along cavity length with cavity scale M=2.5,3.0 and 3.5.

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10a. Abstract. (An abstract should aim to give an informative and concise summary of the report in up to 300 words).

This document constitutes the final technical report under the terms of US Air Force Office of Strategic Research Grant No F49620-98-1-0167. This grant provided funding to undertake an experimental research programme to investigate the acoustic environment of single and tandem box cavities at high supersonic speeds to establish the effects of Reynolds number, Mach number and model scale.

The initial statement of work and planned milestones are reproduced. The status of effort and achievement are reviewed against initial targets. All objectives and milestones have been achieved.

A review of the research carried out is given, sample results provided and conclusions and recommendations from the work are summarised. These summaries provide only a brief précis of the research programme, results and conclusions as detailed accounts are provided in two referenced and published technical reports.

All results from the research programme are available on CD ROMs.

10b. Abstract classification: UNLIMITED	FORM MEETS DRIC 1000 ISSUE 5

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